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MILESTONES OF THE PHENIX EXPERIMENT AT RHIC

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Abstract

The latest PHENIX results for particle production are presented in this paper. A suppression of the yield of high p_t (transverse momentum) hadrons in central Au+Au collisions is found. In contrast, direct photons are not suppressed in central Au+Au collisions and no suppression of high p_t particles can be seen in d+Au collisions. This leads to the conclusion that the dense medium formed in central Au+Au collisions is responsible for the suppression. It is as well found, that the properties of this medium are similar to the one of a liquid. Further measurements provide information about the chiral dynamics of the system.

1 Introduction

Ultra-relativistic collisions, so called “Little Bangs” of almost fully ionized Au atoms are observed at the four experiments (BRAHMS, PHENIX, PHOBOS and STAR) of the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory, New York. The aim of these experiments is to create new forms of matter that existed in Nature a few microseconds after the Big Bang, the creation of our Universe.

A consistent picture emerged after the first three years of running the RHIC experiment: quarks indeed become deconfined, but also behave collectively, hence this hot matter acts like a liquid [1], not like an ideal gas theorists had anticipated when defining the term QGP. The situation is similar to as if prisoners (quarks and gluons confined in hadrons) have broken out of their cells at nearly the same time, but they find themselves on the crowded jail-yard coupled with all the other escapees. This strong coupling is exactly what happens in a liquid [2].

2 High pt suppression

High transverse momentum particles resulting from hard scatterings between incident partons have become one of the most effective tools for probing the properties of the medium created in ultra-relativistic heavy ion collisions at RHIC. Nuclear modification factor, defined as

$$R_{\mathrm{AA}}(p_t) \equiv \frac{\text{Yield in Au+Au events}}{\text{Scaled Yield in p+p events}}, \tag{1}$$

was measured in central and preripheral Au+Au collisions at the four RHIC experiments [3, 4, 5, 6, 7, 8, 9, 10]. The measurements show a high transverse momentum hadron suppression in central Au+Au collisions compared to (appropriately scaled) p+p collisions, while there is no such suppression in peripheral Au+Au or d+Au collisions [11, 12, 13], as shown in the upper plots of Fig. 1. This shows that the suppression is not due to modification of parton distributions in the colliding nuclei.

The nuclear modification factor has been measured for several hadron species at highest p_t: for π_0, and most recently η mesons [14], as shown in the lower plots of Fig. 1. This confirms the above evidence for a dense and strongly interacting matter. On the other hand, direct photon measurements, which require tight control of experimental systematics over several orders of magnitude, show that the high p_t photons in Au+Au collisions are not suppressed [15] and, thus, provide final confirmation that hard scattering processes occur at rates

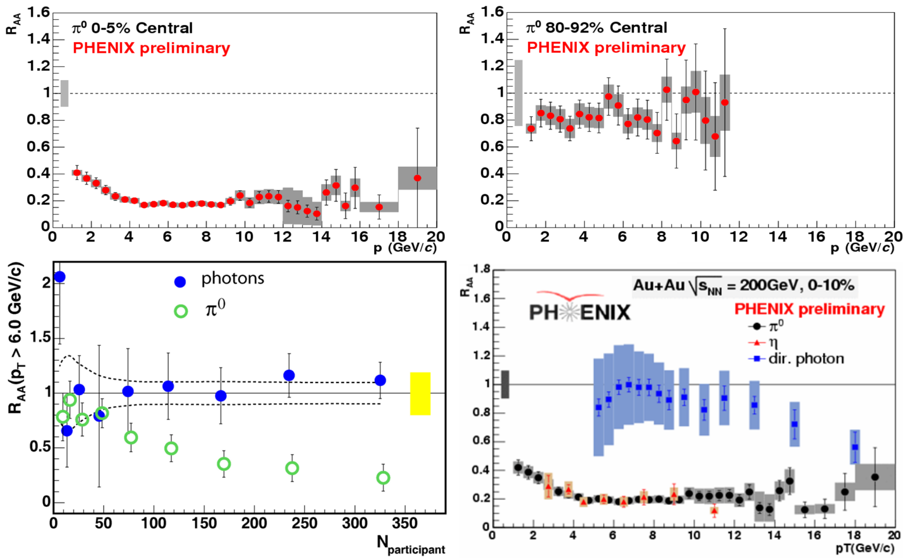

Figure 1: Nuclear modification factor $R_{\rm AA}$ for π_0, η and photon yields in Au+Au collisions as a function of p_t for different centralities (different number of participants). The shaded error band around unity indicate systematic errors.

expected from point-like processes. This observation makes definitive the conclusion that the suppression of high-p_t hadron production in Au+Au collisions is a final-state effect.

3 The perfect fluid of quarks

One of the most important results of RHIC is the relatively strong second harmonic moment of the transverse momentum distribution, referred to as the elliptic flow. The elliptic flow is an experimentally measurable observable and is defined as the azimuthal anisotropy or second Fourier-coefficient of the single-particle momentum distribution $N_1(p)$. The $n^{\rm th}$ Fourier-coefficient is defined as:

$$v_n = \frac{\int_0^{2\pi} N_1(p)\cos(n\varphi)d\varphi}{\int_0^{2\pi} N_1(p)d\varphi}, \tag{2}$$

φ being the azimuthal (perpendicular to the beam) axis of momentum p with respect to the reaction plane. This formula returns the elliptic flow v_2 for $n = 2$.

Measurements of the elliptic flow by the PHENIX, PHOBOS and STAR collaborations (see refs. [16, 17, 18, 19, 20, 21]) reveal rich details in terms of its dependence on particle type, transverse (p_t) and longitudinal momentum (η) variables, and on the centrality and the bombarding energy of the collision. In the soft transverse momentum region ($p_t \lesssim 2$ GeV/c) measurements at mid-rapidity are found to be well described by hydrodynamical models [1, 22, 23, 24, 25]. Important is, that in contrast to a uniform distribution of particles expected in a gas-like system, this liquid behavior means that the interaction in the medium of these copiously produced particles is rather strong, as one expects from a fluid. Detailed investigation of these phenomena suggests that this liquid flows with almost no viscosity [26].

Measurement of elliptic flow of pions, kaons, protons, ϕ mesons and deuterons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, when plotted against scaling variable KE_T (transverse kinetic energy) confirm the prediction of perfect fluid hydrodynamics, that the relatively "complicated" dependence of azimuthal anisotropy on transverse momentum and particle type can be scaled to a single function [26, 27, 28, 29, 30]. On the left plot of Fig. 2 we show this scaling. Mesons and barions gather into two different groups here. If one scales both axes of these plots by the number of constituent quarks of the measured hadrons (as shown on the right plot of Fig. 2), the two curves collapse to one [31]. Thus it appears that quark collectivity dominates the expansion dynamics of these collisions-

4 Heavy flavour

We also have measured electrons from heavy flavor (charm and bottom) decays in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The nuclear modification factor R_{AA} relative to p+p collisions shows a strong suppression in central Au+Au collisions, indicating substantial energy loss of heavy quarks in the medium produced at RHIC energies. A large elliptic flow, v_2 is also observed indicating substantial heavy flavor elliptic flow. Both R_{AA} and v_2 show a p_t dependence different from those of neutral pions. A comparison to transport models which simultaneously describe $R_{\mathrm{AA}}(p_t)$ and $v_2(p_t)$ suggests that the viscosity to entropy density ratio is close to the conjectured quantum lower bound, *i.e.* near

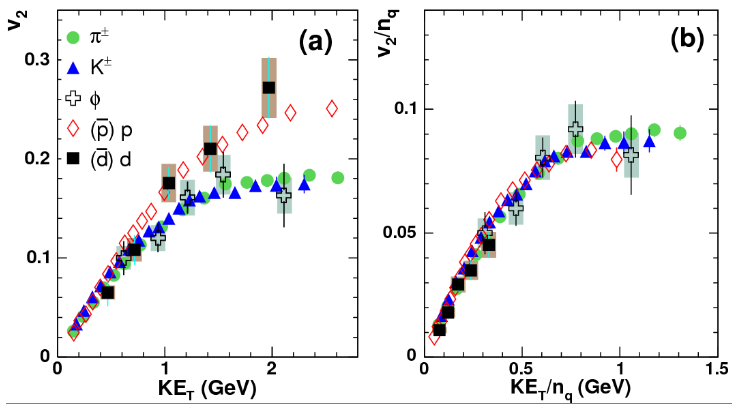

Figure 2: (color online)(a) v_2 vs KE_T for several identified particle species obtained in mid-central (20-60%) Au+Au collisions. (b) v_2/n_q vs KE_T/n_q for the same particle species shown in panel (a). The shaded bands indicate systematic error estimates for $(\bar{d})d$ and ϕ mesons (see text).

a perfect fluid [32, 33, 34], as shown on Fig. 3

We see, that even heavy flavour is suppressed beyond extrapolations from cold nuclear matter effects, and even heavy flavour is flowing similarly to hadrons made out of light quarks. This suggests strong coupling of charm and bottom to the medium [11, 35].

5 Chiral dynamics

Correlation functions are important to see the collective properties of particles and the space-time structure of the emitting source, e.g. the observed size of a system can be measured by two-particle Bose-Einstein correlations [37].

The m_t dependence of the strength of the two-pion Bose-Einstein correlation function λ can be used to extract information on the mass-reduction of the η' meson (the ninth, would-be Goldstone-boson), a signal of the $U_A(1)$ symmetry restoration in hot and dense matter: It is known, that if the chiral $U_A(1)$ symmetry is restored, then the mass of the η' boson is tremendously decreasing and its production cross section tremendously increasing. Thus η' bosons are copiously produced, and decaying through η bosons (with a very long lifetime)

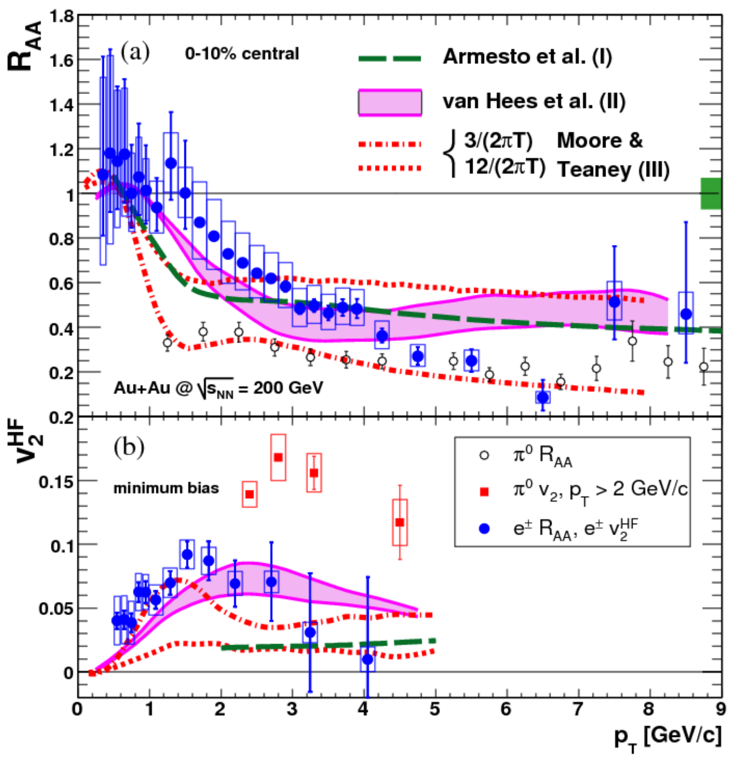

Figure 3: (a) $R_{\rm AA}$ of heavy-flavor electrons in 0-10% central collisions compared with π^0 data [6] and model calculations (curves I [32], II [33], and III [34]). (b) $v_2^{\rm HF}$ of heavy-flavor electrons in minimum bias collisions compared with π^0 data [36] and the same models. Boxes show systematic uncertainty in both plots.

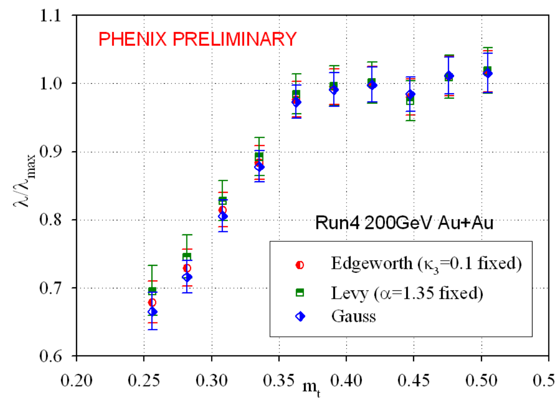

Figure 4: Measured $\lambda(m_t)$ from different methods

into low momentum pions. Hence the strength of the two-particle correlation functions at low relative momenta might change significantly. [38, 39, 40, 41].

PHENIX analyzed [42] two-pion Bose-Einstein correlations with fits to two-pion correlation functions using three different shapes, Gauss, Levy and Edgeworth, and determined $\lambda(m_t)$ from it, as described in refs. [43, 42, 44]. We re-normed the $\lambda(m_t)$ curves with their maximal value on the investigated m_t interval. This way they all show the same shape, as shown in Fig. 4. This confirms the existence and characteristics of the hole in the $\lambda(m_t)$ distribution.

We conclude that at present, results are critically dependent on our understanding of statistical and systematic errors, and additional analysis is required to make a definitive statement.

The PHENIX experiment has also measured the dielectron continuum in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions [45, 46]. The data below 150 MeV/c^2 are well described by the cocktail of hadronic sources. The vector mesons ω, ϕ and J/ψ are reproduced within the uncertainties. However, in minimum bias collisions, the yield is substantially enhanced above the expected yield in the continuum region from 150 to 750 MeV/c^2. The enhancement in this mass range is a factor of 3.4 $\pm$ 0.2(stat.) $\pm$ 1.3(syst.) $\pm$ 0.7(model), where the first error is the statistical error, the second the systematic uncertainty of the data, and the last error is an estimate of the uncertainty of the expected yield. Above the ϕ meson mass the data seem to be well described by the continuum

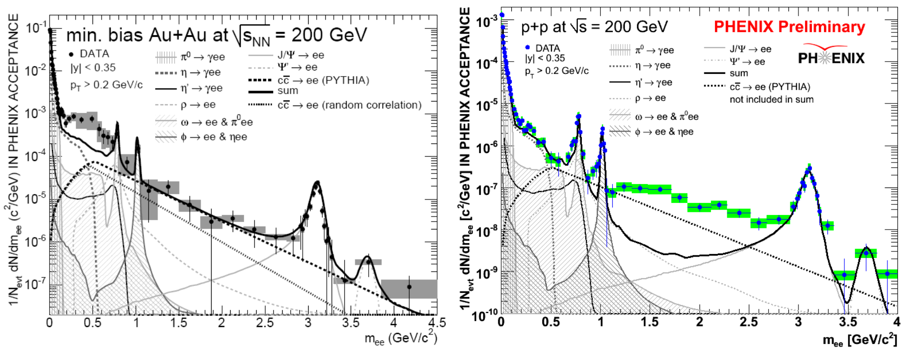

Figure 5: Invariant e^+e^-–pair yield of refs. [45, 46] compared to the yield from the model of hadron decays. The charmed meson decay contribution based on PYTHIA is included in the sum of sources (solid black line). The charm contribution expected if the dynamic correlation of c and $\bar{c}$ is removed is shown separately. Statistical (bars) and systematic (boxes) uncertainties are shown separately; the mass range covered by each data point is given by horizontal bars. The systematic uncertainty on the cocktail is not shown.

calculation based on PYTHIA, as shown in Fig. 5

6 Summary and conclusions

Based on the measurements of suppression of high transverse momentum hadrons and of their elliptic flow, we can make the definitive statement, that in relativistic Au+Au collisions observed at RHIC we see a strongly interacting matter, that has the characteristics of a perfect fluid. We also see signals of chiral dynamics by the enhancement of the dielectron continuum above the expected yield from hadron production and the possible mass modification of the η' meson. Future plan is to explore all properties of the Quark Matter, by analyzing more data and using higher luminosity.

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